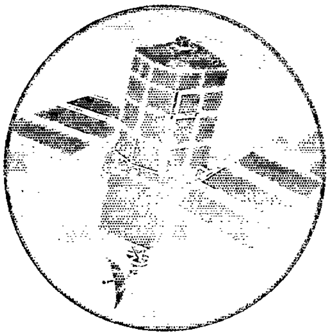
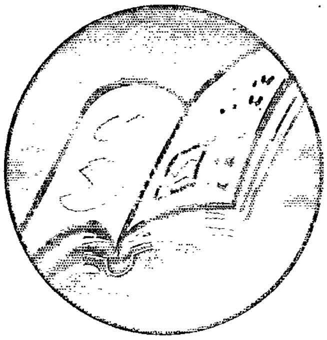
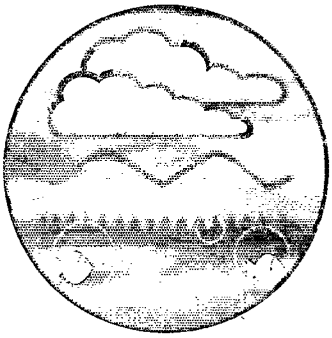
Impact of Nutrients in Estuaries
Phase 2: Summary Report







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Impact of Nutrients in Estuaries - Phase 2: Summary Report

R&D Technical Report P269

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EXECUTIVE SUMMARY

Nutrient enrichment may have obvious, subtle or no biological impact on the aquatic environment, depending on the influence of a number of physical, chemical and biotic factors. This influence is never more difficult to predict than in the dynamic and variable estuarine ecosystem. The complexity of estuaries hinders a clear understanding of cause and effect. This, in turn, makes it difficult for the Environment Agency and English Nature to manage estuarine water quality and conservation status, as required by EC Directives on Urban Waste Water Treatment, Nitrates and Habitats, and other elements of the regulatory framework.

The Agency and English Nature commissioned this review of literature and expert opinion on the impact of nutrients in estuaries as an important step towards delivering the sound scientific foundations on which effective management strategies must be based.

A number of factors influence the nature of nutrient inputs to estuaries. While regulatory control has tended to focus on point-sources, diffuse inputs represent a major challenge. It is notable that nutrient inputs from catchments characterised by diffuse sources, tend to be dominated by nitrogen. Furthermore, it is evident that the physical characteristics of an estuary, particularly freshwater flushing time, determine the extent to which nutrients are available for utilisation by any process. The processes in question, both biological and chemical, play key roles in nutrient cycling, and consequently mediate the cycles of growth and decay in estuaries. In non-light-limited situations the classic estuarine response to nutrient enrichment is an increase in plant growth. However, when light is not available to drive primary production (and where consequently hypernutrification may not lead to eutrophication), physical factors such as hydrodynamics and geomorphology become dominant in determining the extent of other processes, such as denitrification.

Estuaries dominated by phytoplankton (eg. diatom and dinoflagellate blooms), in terms of biomass, are regarded as demonstrating the final stage in a succession of changes driven by excessive and chronic nutrient inputs to estuaries, however there are other, often more subtle, but important, primary impacts. Benthic microalgal communities, compete with phytoplankton for nutrients in shallow waters, and more widely when suspended by turbulent mixing. Macroalgae may also compete with phytoplankton for water-column-nutrients, and, like benthic microalgae, when forming dense mats, may obstruct the exchange of nutrients across the sediment-water interface, and restrict the development of infauna. A change from a low to a high nutrient environment will tend to drive a stepwise shift in community structure from vascular plants, such as seagrasses and saltmarsh vegetation, which tend to have a competitive advantage in low nutrient environments, to phytoplankton. As well as plants, bacteria, bound to sediments or associated with particulate matter in the water column, utilise inorganic nutrients, particularly nitrogen species, and play an important role in the estuarine response to nutrient input.

In addition to the primary (autotrophic) response to nutrient enrichment, there are secondary effects. The most prominent of these are the impacts of oxygen depletion, caused by the increase in organic loading that accompanies the accentuated primary production and subsequent decay of plant material in nutrient-enriched waters. This can have major deleterious effects on benthic macrofauna, but a lesser impact on the more tolerant meiofauna. The primary and secondary impacts of nutrient enrichment can have knock-on tertiary effects, higher in the food-chain. In most cases, however, the complexities of food-web structure and the varying interactions between physical and biological processes in estuaries (which limit the scope to extrapolate findings between different systems), make it extremely difficult to predict the biological response at these higher trophic levels. Estuarine morphology, and, indirectly, the production of toxic sulphide in sediments, may shape the community at these levels.

It appears that, once underway, community changes triggered by nutrient enrichment may be self-perpetuating, and hence not completely reversible without ecological intervention. The lack of field data means that this conclusion can only be provisional, however, the implementation of nutrient controls driven by EU legislation will offer opportunities to further examine the extent to which eutrophication can be reversed purely by reducing the nutrient loading.

With good scientific understanding and relevant monitoring data it would be possible to assess the current nutrient/trophic status of an estuary, set meaningful and realistic objectives, formulate and implement actions to meet those objectives, and measure the success of those actions. However, we currently only have a partial, qualitative understanding of cause and effect, with respect to the impacts of nutrients in estuaries, and this, together with the inadequacy of available data (often collected for other purposes), makes it difficult to set meaningful chemical or biological monitoring criteria, or management targets.

It is therefore not surprising that there do not appear to be any examples of complete management strategies on estuarine eutrophication, although certain elements of such strategies do exist, for example, assessment and classification schemes. These qualitatively, or semi-quantitatively, describe the nutrient or trophic status of estuaries, or distinguish their differing ecological susceptibilities to nutrient impacts (allowing priorities to be identified). A scheme is proposed, in this latter category, as a generic framework for screening the eutrophication-risk of estuaries. The classification criteria are physico-chemical parameters (nutrient input, turbidity, flushing time, etc.). As a broad-brush approach, this would not be applicable in issue-driven situations (eg. SACs, SPAs, etc.), where detailed information has already been collected.

A further fundamental challenge to management is the setting of relevant targets, and the most likely way forward is seen in the development of Ecological Quality Objectives (EcoQO's), as established, conceptually, in OSPAR and EU discussions on environmental protection. Key estuarine communities are identified, and high level objectives established for them, eg. for saltmarshes, it is suggested that there should be no persistent decline in areal coverage or productivity, relative to all other estuarine vegetation, nor increase in plant tissue nutrient levels, over specified timescales. Such nascent EcoQOs clearly need further development and trialling.

The classification and EcoQOs are two key elements of a proposed four-stage process for managing nutrient impacts on water quality and conservation interest, in the estuaries of England and Wales:

- screening to identify priorities;
- assessing, in detail, the status of those priority sites;

- setting specific objectives for the sites;
- taking appropriate action and monitoring to assess progress towards the objectives.

This proposal extends the approach already used to examine estuarine nutrient impacts, in the context of the EC Urban Waste Water Treatment, Nitrate and Habitats Directives, to a more generic and widely applicable process.

The Environment Agency and English Nature are invited to trial this management approach, and to consider recommendations for further research to fill important gaps in their understanding.

KEYWORDS

estuaries, nutrient, conservation, ecosystem, eutrophication, phytoplankton, microalgae, macroalgae, macrophyte, denitrification, flushing time, turbidity, estuarine monitoring, estuarine classification, ecological quality objectives.

1. BACKGROUND

This report summarises the findings of a literature review commissioned by the Environment Agency and English Nature to investigate the Impact of Nutrients in Estuaries. The project had the objective of bringing together the best understanding of the biological consequences of nutrient input to estuaries to support work towards the improvement of water quality and conservation status of estuaries in England and Wales.

The structure of this report mirrors that of the Project Record P2/i639/1, making it easy to "read across", to obtain further details on any particular topic.

In recent years there has been increasing concern about the ecological impact of anthropogenic nutrient inputs to estuaries. This concern has been accompanied by national legislation and international legislation aimed, directly or indirectly, at controlling nutrient inputs and hence their potential biological impact. The most significant regulations in the context of this work result from the EU Urban Waste Water Treatment, Nitrates and Habitats Directives and from agreements reached in the framework of the Oslo and Paris Convention.

Despite this intense interest, and a significant body of scientific research, there remains a considerable lack of clarity about the impact of nutrients on estuarine communities, because it is often difficult to distinguish cause from effect in the wide variety of complex estuarine systems. Synthesising a coherent overview from the wealth of detailed scientific studies is a challenging task. An essential first step is, therefore, to provide a clear view of current scientific knowledge on the effect of nutrients on biological communities in estuaries, especially those that are designated for conservation, and to develop effective approaches to monitoring and management.

The Environment Agency and English Nature commissioned this study to provide the knowledge and tools needed to help them meet their respective objectives for the management of water quality and conservation in estuaries. An initial workshop, in 1995, attended by a cross-section of the academic and regulatory community, assessed present knowledge in England and Wales. This was followed by a comprehensive review of literature and expert opinion on both the current state of knowledge and the best options for management of nutrient impacts in estuaries. The resulting draft report and its recommendations were discussed at a second workshop in 1998. Comments from that workshop are incorporated in the final project record. This technical report provides a summary of the project record, the structure of which it mirrors almost exactly, making it easy to read across where more detailed information is required.

The review of the literature and expert opinions was carried out by the Cambridge Coastal Research Unit in collaboration with four consultants who have experience of issues relating to nutrient impacts in aquatic systems: Dr M. Elliott (University of Hull); Prof. V. N. de Jonge (RIKZ, Netherlands); Dr S. J. Malcolm (CEFAS, Lowestoft); and Dr M. Wilkinson (Heriot-Watt University).

2. EFFECT OF PHYSICO-CHEMICAL FACTORS

Aim: To review nutrient dynamics, and the effects of physical and chemical factors on biological responses in estuaries.

2.1 Introduction

Estuaries are dynamic, variable ecosystems, shaped by a number of physico-chemical factors, which in turn influence the extent and type of any biological responses to nutrient enrichment. This complexity makes it particularly difficult to distinguish between cause and effect.

Estuaries are characteristically dynamic systems, which exhibit a high degree of temporal and spatial variability in environmental conditions. This is driven by changes in river discharge, tides, weather and climate, which result, *inter alia,* in changes to current speeds, turbidity, temperature, and salinity.

The variability in the environmental conditions within and between estuary systems makes it difficult to clearly distinguish the cause and effect relationships between nutrient increases and biological responses in estuaries. Estuaries are also subject to multiple environmental stresses and it can be difficult to determine the precise cause of any observed biological change. Estuaries are a major site for problems associated with inorganic and organic contaminants. They are the recipients of significant quantities of sewage. This leads to direct organic enrichment, the symptoms of which can be confused with those resulting from nutrient input.

This presents major problems for regulators and managers who need to develop the best strategies for monitoring nutrients, and assessing the risk of impact to estuarine communities.

A good understanding of how environmental conditions within estuary systems influence biological responses to nutrients is essential to the development of a strategy for estuary management. It is also important to understand the sources of nutrients and the processes involved in transforming, cycling and retaining nutrients in estuaries.

2.2 Nutrient Inputs to Estuaries

Many factors influence the input of nutrients from land into estuaries but it is clear that the quantity and timing of the input is related to the seasonal hydrological cycle. The relative importance of diffuse and point source nutrient inputs in a catchment, will strongly influence the balance between nitrogen and phosphorus (and silicon) in its estuary, diffuse sources tending to be dominated by nitrogen.

It is possible to divide inputs of nutrients into two categories according to the route of entry to the aquatic environment. These are:

- **point sources** - inputs from specific locations such as the outfalls of industrial plants and sewage treatment works.
- **diffuse sources** - inputs from non site-specific sources such as the catchment, the atmosphere and groundwater.

Point source inputs resulting from discrete discharges are more readily quantifiable, unlike diffuse inputs which can be highly variable, and more difficult to quantify, or even to apportion to anthropogenic causes. Diffuse inputs from land are affected by catchment characteristics such as geomorphology, soil type, land uses, management practices and habitat types, which influence the rate of nutrient export via freshwater run-off. For example, the nutrient exports from urban and agricultural areas are greater than from forests or wetlands.

There is greatest uncertainty about the relative importance of nutrients entering estuaries from coastal waters, atmospheric deposition (of nitrogen only) and groundwater reservoirs. This will depend on the specific characteristics of each estuary. Direct atmospheric deposition rates can be related, for example, to atmospheric output from industry, transportation and agriculture, and the surface area of the estuary.

In general, diffuse inputs are rich in nitrogen and point source inputs (predominantly sewage) can have relatively high phosphorus concentrations. Therefore the relative contributions of diffuse and point source inputs to an estuary affect the balance of nutrient species entering the system. Inputs to estuaries where diffuse sources provide the greatest contribution *tend to* have high N:P ratios, while those where point sources dominate *tend to* have correspondingly lower ratios (although other factors may complicate the situation).

In contrast to nitrogen and phosphorus, silicate is not derived directly from anthropogenic sources but from the weathering of geological material. The magnitude of the silicate input is determined mainly by catchment characteristics but may be influenced by a limited range of man's activities including the continual reworking of agricultural soils.

The freshwater flow into estuaries has an important influence on the scale and composition of nutrient input. Increased flow derived from high rainfall will elevate the inputs from diffuse sources, while the total load from point sources will tend to remain constant in most cases (with the exception of the "first flush" through surface water/combined sewerage outfalls, after long dry periods).

The management of nutrient inputs presents more or less difficulty depending on whether the source is point or diffuse. The control of point sources tends more to be a technical task whereas the management of diffuse sources can require 'costly' large-scale social changes, such as alterations to agricultural practice, urban development or land use.

2.3 Nutrient Retention in Estuaries

The physical characteristics of an estuary will determine the extent to which nutrients are available for utilisation by any process. For example, if the residence time of a nutrient is shorter than the characteristic time for utilisation, then use will be limited. There remains a debate about the most appropriate measure of this 'availability' time, with a developing view that freshwater flushing time may be most appropriate for estuaries to which the dominant nutrient input is from rivers. Estuaries may act as significant sinks for nutrients that would otherwise be biologically available.

The length of time that nutrients remain within estuaries dictates their availability to communities and affects the potential for biological utilisation and impact. A key factor affecting estuarine retention of nutrients is residence time, which can be defined in a number of ways. A view is developing that the best measure of residence (and hence availability) time is the freshwater flushing time, which is the average amount of time that freshwater takes to pass through the estuary. This measure only applies to waterbodies which receive a significant freshwater input, and where this input is the dominant nutrient source. The flushing time is influenced by geomorphological characteristics such as estuary bathymetry, which determines the volume of the estuary, and the freshwater flow rate and tidal regime, which together dictate the rate of water flow through the estuary. Stratification can influence the freshwater flushing time because the influence of freshwater is likely to be restricted to the upper part of the water body i.e. less than the total volume of the estuary.

Geomorphological features such as sills, inter-tidal flats and embayments will also affect the residence time, and hence retention of nutrients, by restricting the flow of water through an estuary, or the exchange of water with the open coast. In addition, the physical characteristics of the estuary will also determine the extent and location of the accumulation of sediments, which will also have a bearing on the sensitivity of the estuary to enrichment.

It has become clear that estuaries can act as a sink for nutrients or at least delay their transfer from rivers to the sea. The physical characteristics of an estuary are an important determinant of the extent of this sink. The importance of sediment area (especially inter-tidal area) relative to volume flow of an estuary will affect the extent to which denitrification (see below) can permanently remove nitrogen from the aquatic environment. Similarly, the physical factors that promote turbidity will influence the extent to which phosphorus can be stored in sediments.

2.4 Nutrient Cycling in Estuaries

Nutrients are subject to continual cycling between different (bio)chemical forms as a result of a variety of biological and chemical processes. These processes mediate the cycles of growth and decay in estuaries, and differences in the rate of particular processes can determine the extent and type of growth that can occur. For example, diatoms can only grow when silicon is available. The dominant processes involving nitrogen and silicon are biological, while those involving phosphorus are chemical.

The **Nitrogen Cycle** is driven by biological processes which convert nitrogen species between three forms. These forms are dissolved inorganic and organic compounds, and the components of cells. The following processes are the most significant:

- **Fixation**:($N_2 \Rightarrow NH_4$)
- **Assimilation**:(NH_4^+, NO_2^- and $NO_3^- \Rightarrow$ amino acids and proteins).
- **Remineralisation**:(PON ⇒ DON)
- **Ammonification**:(DON ⇒ NH_4^+).
- **Nitrification**:($NH_4^+ \Rightarrow NO_2^- \Rightarrow NO_3^-$)
- **Nitrate reduction to ammonia**: ($NO_3 \Rightarrow NH_4^+$)
- **Denitrification**:($NO_3^- \Rightarrow$ gaseous N_2 or N_2O).

  [PON = particulate organic nitrogen; DON = dissolved organic nitrogen]

Denitrification is a key process as it leads to a net loss of nitrogen from the aquatic system.

The **Phosphorus Cycle** is governed by both biological and physico-chemical processes. Biological processes convert phosphorus species between three states: dissolved inorganic and organic compounds and the components of cells. The following processes are involved:

- **Assimilation**:($PO_4^{3-} \Rightarrow$ LOP).
- **Release**: (LOP ⇒ Free POP, DOP and PO_4^{3-}).
- **Remineralisation**: (Free POP, DOP ⇒ PO_4^{3-}).
- **Adsorption**: Phosphate also reacts at, and is adsorbed to, particle surfaces, especially those containing metal oxides and calcium minerals. Phosphate behaviour in estuaries therefore depends on turbidity as well as riverine phosphate concentration. There tends to be significant removal of phosphorus to sediments.

  [LOP = living organic phosphorus; POP = particulate organic phosphorus; DOP = dissolved organic phosphorus]

The **Silicon Cycle**, in contrast to those of nitrogen and phosphorus, is less well defined, as chemical behaviour has not been as intensively studied. Silicate is assimilated by diatoms (and silico-flagellates) to produce skeletal structures which are remineralised through a process of simple dissolution. The rate of remineralisation is slow compared to that of nitrogen and phosphorus.

2.5 Factors Affecting the Biological Response

The main factors affecting biological response in estuaries are the availability of light and nutrients. The physics of estuaries can influence both while external drivers are important in determining the delivery of nutrients to the estuary. When light is not available to drive primary production, the physical factors become dominant in determining the extent of, for example, denitrification and this is related to the hydrodynamics and geomorphology of the estuary.

The only important factors that influence the biological response to nutrient inputs in estauries are those that affect the availability of either nutrients or, for photosynthetic organisms, light. The principal factors are:

- **Freshwater input** affects community responses by delivering nutrients to the estuary or modulating other physical factors such as flushing time and turbidity. Freshwater flow can influence seasonal phytoplankton growth: there may be a relationship between the timing of freshwater flow events and the spring bloom of phytoplankton.

- **Flushing time** (see above) influences the time that nutrients are available to communities. Longer flushing times increase the potential for a biological response. Links have been established between flushing time and the size of phytoplankton blooms. At the other extreme, in rapidly flushing estuaries there may be insufficient time available for the development of phytoplankton blooms.

- **Turbidity** in an estuary will affect community response by influencing the light available to photosynthetic organisms. The maximum depth to which phytoplankton can be mixed and still have sufficient light for net photosynthesis is termed the critical depth; phytoplankton growth takes place in turbid water when the critical depth is greater than the water depth.

  Turbidity also influences where the strength of any bacterial activity will be greatest, as the majority of bacteria in estuaries are attached to particles. Many estuaries have a zone characterised by high turbidity, where nitrification and denitrification occur at maximum rates.

- **Tidal regime** influences the strength of water movement, sediment resuspension and turbidity. High-energy, macrotidal systems generally have a lower phytoplankton abundance than systems with less tidal energy, and thus nutrients generally behave conservatively (ie. are neither removed from, or added to, the water). Resuspension can also affect the stability of the sediments and the development of benthic macro- and micro-algal mats.

- **Stratification** is often an important factor in the formation of phytoplanktonic blooms in particular types of estuary, and this can lead to macro-biological impacts.

- **Estuary bathymetry** (in conjunction with turbidity) influences the relative response of benthic and pelagic algae. Phytoplankton have a competitive advantage over benthic algae in deeper systems, where benthic plants are limited by light. Benthic macro- and micro-algae that can survive in the periodically illuminated inter-tidal regions have an advantage over phytoplankton in turbid estuaries, although the distinction between phytoplankton and microphytobenthos is often difficult to establish.

Temporal variability of these factors is marked and relates to short and longer-term changes in weather/climatic conditions. For example, rainfall can influence all of the features which depend on water movement, wind can have a major influence on turbidity and cloudiness can affect the amount of sunlight.

3 BIOLOGICAL IMPACT OF NUTRIENTS

Aim: To review the effects of nutrients on the communities and habitats in estuaries and to review the effects of communities on nutrient dynamics

3.1 Introduction – Hypernutrification and Eutrophication

It is important to distinguish between hypernutrification and eutrophication. Nutrients are not of themselves toxic, and therefore a simple addition of nutrient to an estuary may not necessarily cause a problem; nutrients are essential for the organisms that make up the estuarine ecosystem. It is the consequences of the addition of nutrients, given favourable conditions for utilisation, which can lead to problems with water quality and the health of the ecosystem.

The impacts of, and responses to, nutrient enrichment can be divided into the following distinct types:

- **primary impacts** are the responses of the autotrophs and heterotrophic bacteria that are the primary users of the (inorganic) nutrient resource; this is expressed in terms of increased production and/or changing species dominance
- **secondary impacts** arising from organic enrichment (e.g. oxygen depletion following the bacteria-mediated decay of primary producers, which have previously undergone increased growth)
- **tertiary impacts** on the top trophic levels through changes in food availability and food web structure. Changing food availability can lead to both increases and decreases in production at the highest trophic level. An increase might be considered beneficial depending on the conservation, or other (eg. fisheries) objectives for an estuary.

The distinction between nutrient enrichment and its biological impacts is made clear in relevant EU Directives (Nitrates and Urban Waste Water Treatment) and the OSPAR Strategy to Combat Eutrophication. In defining eutrophication, these recognise the difference between simple nutrient enrichment and the undesirable consequences that can result, and seek to control the latter through establishing measures which limit the former. There have been considerable difficulties in the implementation of the EU Directives and it remains to be seen whether the OSPAR strategy will be effective. One difficulty with the legislation is that the aspiration to control precedes a sufficient scientific understanding of the problem. Furthermore, there is a commonly held view that nutrients can, and should, be treated in the same way as hazardous chemicals.

Although a range of potential impacts can arise from nutrient enrichment, eutrophication should not be regarded exclusively as a detrimental process as promoting increased productivity can have ecological benefits. Indeed the high inputs of nutrients typical of many estuaries have resulted in these ecosystems being amongst the most productive. However, high nutrient loading is not typical of most estuaries in England and Wales.

3.2 Impacts on Autotrophs and Bacteria

3.2.1 Phytoplankton

Phytoplankton are microscopic plants that, like other plants, require light and a supply of inorganic nutrients to grow. Of approximately 15 classes of algae, the diatoms and dinoflagellates together, with a broad grouping of flagellates, provide the most important phytoplankton species. Phytoplankton blooms are regarded as representing the final, and largely irreversible, stage in a succession of changes driven by excessive and chronic nutrient inputs to estuaries.

The response of phytoplankton to nutrients can generally be explained in terms of the interplay between light, nutrient availability and water mixing.

Light is the fundamental energy source for all plants. The quality and quantity of light vary strongly with depth. In the presence of sufficient light and (non-limiting) nutrient concentrations plants will grow.

Mixing of the water column occurs if the turbulent kinetic energy, generated by tidal motion, is sufficient to overcome the effects of buoyancy resulting from freshwater input or solar heating. If mixing occurs, suspended particles, including phytoplankton, will be circulated throughout the entire water column. If not, the water column will become vertically stratified (layered), effectively partitioning material into upper and lower layers. The amount of light received by phytoplankton is dependant upon sub-surface irradiance which depends on their position within the water column. If vertical mixing is such that phytoplankton receives insufficient light there will be no net growth. Consequently, even in a hypernutrified estuary phytoplankton growth will not occur if light is limiting, so hypernutrification should not be assumed to be synonymous with eutrophication.

Increases in phytoplankton biomass in the water column arise as result of growth, and reductions in biomass result from a variety of loss processes. The loss terms include respiration, grazing and cell lysis. They also include sinking and advection (flushing). These latter two terms may also act as gain terms and therefore increase biomass. The balance between these processes will determine phytoplankton biomass in the water column, and will act over a wide range of time scales (hours to months)

Total inorganic nitrogen and/or phosphorous concentration will set a limit to the maximum potential phytoplankton biomass while silicate is more critical for diatoms. Based on measurements of the elemental composition of algal cells the "Redfield Ratio" is widely believed to define the growth requirements of phytoplankton. An examination of the external concentrations of nutrients, for departures from this ratio (C:N:P of 106:16:1) can be used to determine which nutrient is likely to be limiting for growth. Nutrient enrichment that results in a shift in the ratio of plant nutrients may also drive shifts in species composition, particularly from diatoms to flagellates when nitrogen is in excess. The shift from diatoms to flagellates may have major impacts on community structure and the fate of phytoplankton carbon. A diatom-dominated system tends to favour a foodchain with higher trophic levels dominated by fish. Flagellate- dominated assemblages tend to favour the recycling of carbon, and may result in a food chain encouraging less desirable top level predators.

Phytoplankton may act as a sink for anthropogenic nutrients and so present a barrier to export to the coastal zone. However, nutrients may be exported from estuaries incorporated into plant matter and support subsequent growth after remineralisation off-shore.

The potential fate of settled phytoplankton carbon is remineralisation through heterotrophic activity, through which it may contribute to the generation of anoxic conditions, and ultimately the release of toxic chemicals, such as ammonia or hydrogen sulphide into the environment.

Phytoplankton represent the final stage in the succession resulting from anthropogenic nutrient input to previously low-nutrient, macrophyte-dominated environments. The view that external cellular nutrient concentrations control growth may not always hold. The internal nutrient concentration (Cell Quota) may exert a direct control on growth rate and may differ from the external nutrient concentration. Consequently, care should be taken in interpretation of ambient nutrient concentration in relation to phytoplankton biomass and growth.

3.2.2 Microphytobenthos

The benthic microalgae comprise primarily diatoms and flagellates, which may on occasions form dense microbial mats in close association with bacteria and microheterotrophs. These may obstruct the exchange of nutrients across the sediment-water interface.

Benthic microalgae compete with phytoplankton for nutrients in shallow waters, and more widely when suspended by turbulent mixing, their high rates of photosynthesis giving them a competitive advantage in turbid waters.

Gain and loss terms for these plants are similar to those for phytoplankton, although sinking and resuspension do not apply to benthic microalgae attached to sediment particles. Seasonal variability in biomass and species composition result from changes in nutrient availability. Spatial variability in total nutrient efflux (and nutrient ratios) from the sediments may explain the spatial heterogeneity in microphytobenthos abundance. With an adequate supply of silicate, diatoms, like all other taxa, respond to increased nitrogen and phosphorus loading with an increase in growth.

The role of dense, epiphytic, algal mats are important. They can act as barriers to the exchange of nutrients across the sediment water interface. They may deplete water column nutrients and indirectly compete with phytoplankton especially in shallow regions of estuaries. With sufficient turbulent mixing, benthic microalgae may be suspended resulting in direct competition with phytoplankton.

The relative contribution of phytoplankton and benthic microalgae to overall estuarine productivity depends on a range of factors including water column turbidity, availability of a suitable substrate and mixing. Relatively high rates of photosynthesis may be achieved by benthic microalgae in turbid estuaries, compared with light-limited phytoplankton. However, other factors such inorganic carbon supply may limit growth of benthic microalgae in intertidal regions.

3.2.3 Macroalgae

These multicellular attached plants are primarily supplied with nutrients from the water column where they compete with phytoplankton, but may also obtain nutrients from sediments and can act as a barrier to water column nutrient replenishment. When forming dense mats they may inhibit exchanges between sediment and the water column and restrict infauna development.

Species may be divided into the 2 groups. The fast-growing, opportunistic 'r'-dominant species and the slower-growing, 'k'-dominants. They generally grow attached to stable surfaces but some may survive 'loose lying' or attached to small stones on tidal flats. Nutrients are derived primarily from the water column although their proximity to the sediment water interface means they make use of newly-released nutrients from the sediment. Several inter-related factors influence their growth including bathymetry, vertical mixing, sub-surface light regime and substrate type. Many observations confirm rapid increases in the growth rate and coverage of opportunistic 'r' dominant species in response to increases in nutrient load.

Macroalgae may act to reduce water column nutrient concentrations, or act as a barrier preventing some nutrients reaching the water column after remineralisation and efflux from the sediments. Macroalgal mats may also promote the development of anoxic conditions in the sediment on which they live, through the production of abundant organic material; and the physical smothering of the sediment surface. This can lead to a decline in the infauna.

3.2.4 Vascular plants

These plants, particularly seagrasses and saltmarsh vegetation, have competitive advantages in low nutrient environment due to the presence of roots or in some cases root associated communities of nitrogen fixing bacteria. High nutrient concentrations in the water may therefore erode this advantage.

Much research has been carried out on seagrasses or 'submerged aquatic vegetation' (SAV). Under high nutrient conditions other plants tend to compete better for available resources, and especially light. High nutrient inputs may also have indirect effects, e.g. through promoting the growth of epiphytic or leaf-fouling animal species, which cause shading and also restrict nutrient exchange at the plant-water interface.

Dead vascular plant material tends to decay slowly resulting in an oxygen demand. Its potential for promoting later in the year tends to be greater than that of other plant communities. Indirect effects on ecosystem response to nutrient input include promotion of microbial nutrient cycling.

The role of saltmarsh plants in nutrient dynamics is less well understood than that of the seagrasses. They may act as sinks or sources of organic matter or inorganic nutrients. The response may depend on saltmarsh maturity and tidal height. Although saltmarshes are generally regarded as nutrient-limited (either nitrogen or phosphorus), the lack of long term studies limits our understanding.

3.2.5 Comparative responses from Autotrophic Taxa

All autotrophs require inorganic nutrients and light to grow. A shift from a low to a high nutrient environment will lead to a stepwise shift in community structure from seagrasses to phytoplankton. The shift appears to be irreversible but lack of field data means this conclusion can only be provisional. Different abilities to cope with nutrient uptake under limiting or non-limiting conditions will determine the overall response of the autotrophic community.

As nutrients increase the autotrophic community tends to shift to light limitation from nutrient limitation, and faster-growing, opportunistic species increase, stepwise, at the expense of slower growing forms.

A typical sequence of response to increasing nutrient input is from seagrasses to slow-growing macroalgae to fast growing macroalgae to phytoplankton (often bloom forming varieties). However, the details may vary depending on local conditions. Once the sequence of changing plant community structure has begun it becomes self-propagating and very difficult to reverse.

Feedback effects reinforce some of these processes. For example:

- As phytoplankton biomass increases, turbidity also increases, reducing light supply to benthic forms
- The increased organic enrichment of sediments due to more rapid breakdown of faster growing plants results in increased anoxia, increasing the rate of nutrient efflux
- The reduction in sediment-binding benthic algae results in increases in sediment resuspension further reducing light availability to benthic forms
- Increased microalgal biomass following nutrient enrichment may support large grazing communities, such as mussel beds, which initially retain but ultimately excrete and regenerate further supplies of plant nutrients.

3.2.6 Bacteria

Bacteria (heterotrophs) as well as autotrophs utilise inorganic nutrients and especially nitrogen species and play an important role in the estuarine response to nutrient input. They may be sediment bound or associated with particulate matter in the water column.

The increased availability of a specific inorganic nutrient will increase the activity of a functional group (e.g. nitrifiers and denitrifiers).

Interactions between different functional groups may occur with one functional group providing a substrate suitable for growth of another. The response of bacteria to nutrient input is complex and it is difficult to generalise. They may reduce the impact of increased nutrient input as they promote coupling between nitrification and denitrification, leading to export of gaseous nitrogen from the system.

At high levels of organic loading, especially when pulsed, bacterial oxygen demand promotes anoxia, which in turn effects other bacterial processes and may inhibit coupling. This promotes nitrogen retention within the system, and may support continued plant growth, especially by the phytoplankton.

3.3 Impacts on Benthic Communities

Benthic infauna are primarily subject to the secondary effects of nutrient enrichment and may act to counter or augment the negative effects of enrichment. Severe organic loading, resulting from excessive nutrient inputs, is likely to have major deleterious effects on benthic macrofauna, but a lesser impact on the more tolerant meiofauna.

The main effects of nutrient enrichment on benthic communities are indirect, arising from increased organic loading, with consequences for oxygen availability. In the case of benthic algal blooms these will affect the balance between burrowing and surface-living organisms, and the physical binding and structure of the sediment.

The changing structure of the benthic community, following increased loading with organic matter, is well known. The initial response of an increase in biomass and productivity is followed by a proliferation of small fast-growing species. As the thickness of the upper oxygenated sediment layer decreases the fauna moves closer the surface and burrowing animals may leave their burrows.

The benthic community may respond in different manners to nutrient enrichment or more specifically increased organic loading. It may exhibit different tolerance levels to anoxia, with behavioural changes following depletion of oxygen. The duration, frequency and timing of oxygen depletion events influence the level of impact.

Benthic communities may play an important role in nutrient cycling through:

- promoting physical fluxes of water -borne nutrients;
- grazing and controlling algal biomass;
- excreting further nutrients which become available for plant growth;
- bioturbation which promotes aeration of sediments with important consequences for nutrient recycling. It specifically contributes to the process of benthic-pelagic coupling which is a critical process in determining the estuarine response to nutrient inputs). Benthic-pelagic coupling is affected by bathymetry and water column vertical mixing process. Dense communities of filter feeding benthic species (e.g. mussel or oyster beds) have important impacts on nutrient cycling.

Anoxic condition, resulting from the increased input of organic material to the benthos, may lead to a reduction in benthic fauna, with positive feed back promoting the further production of organic matter in the water column.

3.4 Impacts on Higher Trophic Levels

While community shifts may occur, the complexity of food-web structure makes it extremely difficult to predict the biological response to nutrients at higher trophic levels. Estuarine morphology, and, indirectly, toxin-production in sediments, may shape the community at its higher levels.

The complexity of food-web structure makes it extremely difficult to predict the biological response to nutrients at higher trophic levels. A phase-shift may occur, for example, from a benthic-dominated food chain to one dominated with filter feeding bivalves i.e. a planktonic food chain. Estuarine morphology can play an important role in providing habitats that select for particular communities, including higher level consumers. Indirect effects on community structure may occur as a result of toxin production in sediments, which can affect the palatability of prey.

3.5 Recovery from Nutrient Enrichment

There have been few detailed studies of estuarine systems recovering from nutrient enrichment, although the implementation of nutrient controls driven by EU legislation offers opportunities to improve understanding. It is suspected that, once underway, many changes associated with enrichment may be self-perpetuating, and that reducing nutrient loading alone maybe insufficient to return the system to its original community

In addition to understanding how estuarine communities are affected by nutrient enrichment, there is also a need to understand how communities may recover from nutrient impacts in order to provide for effective management. However, the understanding of how an estuary recovers from impact is still very poor largely because there are few, if any, examples of systems being studied in recovery.

A major concern with respect to the recovery of communities is that many of the responses to enrichment may be self-perpetuating. This might include changes in the type of dominant plant, in benthic-pelagic coupling or in the food web. An example of such a change is where the growth of opportunistic green macro-algae covering inter-tidal areas leads to winter storage of nutrients in sediments, which are released in the following spring to support further growth. This situation may be difficult to reverse. Without major physical intervention, the simple reduction of external nutrient input alone will not change the current status. Birds that depend on particular food organisms in inter-tidal areas may be permanently excluded from particular environments due to changing macro-faunal communities. In such circumstances reversal may not be possible and new objectives for that environment may need to be accepted.

It is clear that there is little information available about the recovery of estuaries following a reduction in nutrient input but that opportunities for such studies will result from the implementation of measures under the EU Urban Waste Water Treatment, Nitrates and Habitats Directives

3.6 Conclusions

In non-light-limited situations, estuaries respond to enrichment by anthropogenic plant nutrients by an increase in plant growth. With increasing nutrient input, a stepwise shift in the plant community is likely to occur resulting in a plant community dominated by phytoplankton. In a light-limited environment, additional nutrient input will have minimal effect on plant growth. Therefore, a hypernutrified estuary is not necessarily a eutrophic estuary.

Increases in organic matter production, a secondary effect of increased nutrient input, will have direct effects on other estuarine biota. Complex interactions between physical and biological process in estuaries prevent the generalisation of results from field studies, although common features are apparent. The responses of higher trophic levels to nutrient enrichment are difficult to predict.

The extent to which recovery is possible is unknown due to the lack of detailed case studies. There is a concern that the deleterious consequences of nutrient enrichment are not reversible without major ecological intervention.

The response of estuaries to increased (anthropogenic) nutrient input is complex.

There are some underlying principles that can be of use in understanding, and aiding the prediction of, the response. Specific field and experimental studies have contributed to an improved understanding of particular systems, but caution should be exercised in extrapolating either from one estuary to another or from experimental studies to the field.

All plants require light, and when it is the factor controlling phytoplankton growth and productivity, additional nutrients will not effect growth. In the presence of sufficient light the effect of increased nutrient input is to stimulate plant growth and increase production and biomass.

In all systems spatial and temporal variability in physical processes, and especially turbulent mixing, will exert a major influence on planktonic and benthic communities.

In low nutrient estuaries the addition of extra nutrients will stimulate plant growth. With increasing nutrient loading, a stepwise shift in the nature of the plant communities is likely to occur from seagrasses and saltmarsh through to systems dominated by phytoplankton.

The microbial heterotrophic community, including bacteria, play a critical role in nutrient cycling and recycling in estuaries within the water column or bottom sediments. For example, it may act to ameliorate nitrogen input through denitrification or, in other circumstances, may exacerbate the problem. Respiratory oxygen demands can generate anaerobic conditions leading to indirect and direct effects on the biota.

Foodweb complexity, and a poor understanding of the links between physical and biological processes, severely limit our ability to predict the effects of anthropogenic nutrient inputs at higher trophic levels. Predators may act to disguise the increased plant growth resulting from increased nutrient inputs through grazing. Shifts in the nature of plant communities may result in major changes in predatory species.

4. MONITORING & MANAGEMENT APPROACHES

Aim: To review existing approaches to monitoring and managing nutrient impacts in estuaries.

4.1 Monitoring Approaches

It has proved difficult to set meaningful criteria or targets, either in chemical terms, relating to nutrient concentrations, or in biological terms, relating to the perceived symptoms of eutrophication, against which compliance can be monitored. The best monitoring approach is therefore likely to form part of a research programme that is based on the testing of a clear hypothesis. It may be necessary to begin this process on a site by site basis.

The most commonly used approaches for monitoring, in relation to nutrients and eutrophication, consist of a combination of field sampling and assessment. The particular assessment techniques used depend on the specific focus of the monitoring. Historically, most effort has been put into monitoring nutrients, which are relatively easy to measure (though difficult to measure in a consistent and valuable way), rather than biological response parameters, which can be more complex to measure.

Given finite resources, all field surveys represent a compromise between the need to collect information of sufficient spatial and temporal resolution, and available effort. Traditional surveys by land and boat remain the most commonly employed approach but automated systems are likely to be increasingly used following the development of relevant sensing technology. In the case of monitoring nutrient concentrations and biological parameters such as chlorophyll (as a measure of phytoplankton biomass), these new advances will allow meaningful monitoring to take place for the first time. Lack of temporal resolution has presented a major challenge to understanding the dynamics of estuarine ecosystems.

Interpretation of field data on nutrients can pose some difficulty. There are two techniques that can be employed for studies at the scale of an estuary; these are:

- **nutrient/salinity plots** used to observe the deviation from linear mixing between a river and a marine end-member concentration;
- **nutrient budgets (mass balances)** which compare the inputs and outputs of an estuary.

Both techniques seek to assess the loss or addition of nutrients, which imply the action of particular processes in all, or in certain sections, of an estuary.

Monitoring chemical and physical parameters is well advanced, but relevant measurements of biology are often lacking. Significant attention should be given to the development of cost effective measures of biological processes and populations/ communities present. The most appropriate biological indicators relate to those organisms symptomatic of trophic change, ie phytoplankton blooms, epiphytic algal development, intertidal algal growth, or changes in benthic communities, fish populations and bird populations.

The biological monitoring of eutrophication will only improve following the adoption of specific hypotheses, or the development of ecological quality objectives (see below) for particular situations.

To assess trophic status, it is important to understand how growth may be limited by nutrient concentrations. Five groups of techniques are well established, but there is still a need to understand how these may be used in the context of eutrophication assessments. The techniques are: micro/mesocosm experiments; algal tissue nutrient concentration; molar nutrient ratios; half saturation constants; and other bioassays.

Numerical models are another potentially useful tool for assessing the nutrient and trophic status of estuaries. However, they also suffer from deficiencies, like other approaches, including a lack of clarity about the hypothesis being tested (models are developed that describe water movement rather than nutrient-ecosystem interactions), and insufficient data for proper validation. A simple modelling approach was recommended for use in assessments made under the EU Urban Waste Water Treatment Directive. This took into account the likely availability of data, and, appropriately used, is adequate for this limited purpose, although it cannot be applied simply at an estuary scale.

4.2 Data Adequacy

The adequacy and availability of relevant data for monitoring and management of estuary water quality, and to support the setting of conservation objectives, with respect to nutrients and eutrophication, is frequently poor. There is a case for the more consistent, hypothesis-based monitoring of the English and Welsh estuaries.

Although a holistic picture is not available, data is rarely sufficient for an estuary to answer specific questions about nutrient or trophic status. This situation results from the lack of specific hypothesis-driven monitoring, and consequently reliance has to be placed on data collected for other purposes. However, comparison of 'similar' estuaries is often hindered by inconsistent sampling (e.g. different spatial and temporal scales) and analysis (e.g. different nutrient species are determined). In addition, it is sometimes simply difficult to access the relevant records. These problems are being overcome by more careful consideration of the purposes to which data can be put, and improved access, through the use of information technology.

Inadequate analytical quality control and quality assurance (AQC/QA) of the data can also limit the use of existing information. This problem is diminishing as a result of national and international inter-comparison and laboratory accreditation.

The inherent variability of estuarine systems makes it difficult to distinguish between infrequent events and the onset of permanent ecological change. This situation will improve with a better understanding of estuarine systems, and with the development of a clearer focus on the objectives to be met. This has already happened to an extent for areas that now have special status with respect to conservation.

Most of the available information regarding nutrients and enrichment symptoms relates to the larger estuaries, or those systems where there is already perceived to be an enrichment problem. There is little, if any, data collected from smaller estuary systems, and the 'low-nutrient' estuaries which might be regarded as the most vulnerable to changing nutrient inputs (even small increases).

4.3 Approaches to the Management of Estuaries

> ***The management of estuaries depends on having the right information, and the ability to assess current status, set objectives and measure the success of actions implemented to meet those objectives. There are a number of approaches that have been used for some aspects of this process, but this project has not identified any examples of a complete management system, including the important review and feedback mechanism.***
>
> ***A fundamental challenge to management is the setting of relevant targets and the most likely way forward is seen in the development of ecological quality objectives.***

An understanding of the current nutrient and/or trophic status can been derived from two related approaches. The first is an *assessment approach* where information is brought together for collective expert judgement. The second is a *classification approach* which is based on expert judgement but attempts to build in a degree of objectivity. The first approach has been adopted by NOAA in the USA and is being discussed in the framework of the OSPAR Convention for application to maritime waters. The second approach of classification has been proposed and tried in a number of different contexts.

4.3.1 Assessment Approach

> ***Assessment approaches provide a qualitative way of describing the broad state of estuaries with respect to nutrients and the undesirable symptoms of eutrophication.***

NOAA (USA) has carried out a national assessment of estuarine eutrophication involving the collation of data for a suite of indicators and response ranges. Information was collated and presented for each: 1) salinity band for all estuaries in the region collectively; 2) mixing zone within individual estuaries; 3) salinity band for individual estuaries. These three approaches and methods of presentation were also used to describe the temporal trends in the eutrophication indicators, in an attempt to demonstrate whether conditions were improving, worsening or had remained unchanged.

4.3.2 Classification Schemes

Classification schemes provide a semi-quantitative way of distinguishing between estuaries of differing susceptibility, but rely on indirect considerations. They can be of value in setting priorities.

As a means of assessing the potential impact from nutrients in different estuarine systems, several authors have proposed schemes to either classify estuaries on the basis of their susceptibility to enrichment (determined by physical characteristics), or their water quality/biological response. Classification schemes can play a valuable role where they are used as screening tools for prioritising action/focusing attention, however, are often heavily criticised if they are established purely for apparently academic purposes.

4.3.3 Hindcasting

Hindcasting (assessing historic nutrient/trophic status) is a technique that can be used to set a context for present management action, but cannot be used as a simple way of setting targets for nutrient and trophic status.

Although the philosophy may be questionable, it is theoretically possible to use hindcasting (assessing historic nutrient and/or trophic status) as a tool to support the setting of objectives for the management of estuarine ecology. However, rather than using it to simply identify a past nutrient/trophic status as the target for management, it may be more useful in helping to give historical perspective to present conditions. There are various methods of hindcasting. A common method has been the use of catchment export modelling to assess historic nutrient inputs to an estuary.

Hindcasting ecological status is more complex but attempts have been made through the use of palaeoecology (predominantly the identification of diatom fossils found in sediment cores), and empirical models (regression models of physical factors and biology), which assume simple relationships that are directly reversible. It is unlikely that any natural ecosystem behaves in this mechanistic way and attention is moving to the use of models describing the complex behaviour of the whole ecosystem.

The potential role of hindcasting to directly set targets for estuarine management should, therefore, not be over-estimated.

4.3.4 Ecological Quality Objectives

Ecological Quality Objectives (EcoQO's) provide a framework for making decisions about actions needed to manage or protect aspects of an ecosystem. Scientists in the Netherlands and Norway have taken a lead in developing EcoQOs for a variety of purposes, but it is considered that further development and trial application is needed before they can be fully integrated into management regimes. However, the concept is now established in both OSPAR and EU discussions about environmental protection, and is implicit in many current EU Directives.

The following set of ecological targets (which still require further development) have been developed for the Trilateral Governmental Wadden Sea Conference, and serve as an example of the approach. The first two, which are water quality targets, relate to the second two, which are ecological quality targets.

- **Nutrients Target 1:** Winter (January/February) concentrations of Inorganic nitrogen and reactive phosphate in a fixed mixture of riverine and marine waters in sector [xx] should be reduced to [xx] μmol dm^{-3} by the year 2010;
- **Nutrients Target 2:** The molar N:P ratio should be within the range 10 to 30;
- **Phytoplankton Blooms:** The length (duration) of *Phaeocystis* blooms must be reduced;
- **Macroalgal mats:** In sector [xx] (i.e. site specific) the average coverage with algal mats should not exceed [xx] (area to be determined).

It is not clear how the specific water quality targets might be derived, but it is likely that hindcasting would play a role.

5 PROPOSED APPROACH FOR ASSESSING NUTRIENT IMPACTS

Aim: To propose approaches for the monitoring and management of the impact of nutrients in estuaries.

5.1 Proposed Assessment, Monitoring and Management Protocol.

To develop an effective regime for the protection of water quality and conservation interest from nutrient impacts, in the estuaries of England and Wales, a four-stage process has been recommended:

- *a screening process to identify priorities is followed by*
- *detailed assessment of status of the priority sites, then*
- *specific objectives are set for the sites, and*
- *action is taken and monitoring conducted to assess progress towards the set objectives.*

It must be remembered that legislation such as the EU Nitrates, Urban Waste Water Treatment and Habitats Directives have already driven us to follow this route. The proposal provides a more generic and widely applicable process.

The review project concluded that a common approach could meet the requirements of both the Environment Agency and English Nature for the monitoring and management of water quality and conservation interest. It is particularly important to identify those estuaries where the actual, or potential for, ecological change from enrichment is greatest, in order to ensure that these receive the earliest attention.

The recommended protocol for identifying and protecting the estuaries which are showing signs of the adverse effects of enrichment is divided into the following four stages:

1. **Screen estuaries for symptoms of hypernutrification and eutrophication**: This involves a broad overview of estuaries to determine whether they exhibit symptoms of eutrophication or hypernutrification. To help make this decision a variety of criteria can be used, including:

    - the list of factors used in the proposed classification scheme (see 5.2 below),
    - the criteria and practical work already done in support of the UWWT and Nitrates Directive,
    - work already done under the Habitats Directive to designate SACs and SPAs,
    - a set of generic Ecological Quality Indicators that can be derived for this purpose.

    The screening process is not a new exercise, as much has already been done to support the legislation outlined above. This proposal formalises and consolidates existing efforts into a more comprehensive and systematic approach for the estuaries of England and Wales.

2. **Assess the biological symptoms from available data and evaluate the link to nutrient enrichment:** The second stage in the protocol involves an examination of the biological responses in those estuaries where symptoms of eutrophication have been observed. As part of this biological assessment it will also be necessary to describe clearly the quality of the available data, and identify the adequacy of the current levels of monitoring in the estuaries under investigation. A proposed protocol for this assessment involves the description of the biological characteristics analysed, their parameters, the analytical techniques used, and their levels of accuracy. It is necessary to determine whether nutrient enrichment is the causative factor and assess the status of available physical and chemical data. To do this the physical features of the estuaries, and the characteristics of nutrient input, need to be considered. Following the assessment of current status and the extent of any link to nutrient input, it may be necessary to conduct a risk assessment, to identify the potential impact of increasing nutrient inputs. This could be achieved using classification and response-susceptibility criteria.
3. **Set Ecological Quality Objectives based on a detailed assessment of desired outcome:** For a given site it will be necessary to establish a set of objectives, which reflect the desired status for the site. This set of EcoQOs need to be based on the specific biological response determined for the site, and should differ from the generic indicators that were used for the screening exercise. Nevertheless the table below (see 5.3) can be seen as a starting point for the development of relevant objectives.
4. **Measures and Monitoring:** Following the identification of EcoQOs, action will be taken to maintain or achieve the targets and a monitoring programme established to assess progress towards the objectives. The assessment carried out in step 2 will determine the extent of monitoring required for a particular estuary, or part of an estuary. It is important that monitoring includes both biological parameters, and the factors determining the availability of nutrients. Once the EcoQO is reached then the extent of monitoring can be reduced to surveillance to determine any change in the risk to that site i.e. any change in the nutrient load.

5.2 Proposed Estuary Classification Schemes

The proposed estuary classification scheme has been developed in an attempt to provide a generic framework for the screening of estuaries for their ecological susceptibility to nutrient impacts. While it does not provide a complete answer it does guide expert judgement towards robust conclusions. The classification scheme is not required for the management of specific and positively-identified issues, but it does allow a broad brush assessment to be completed for the many estuaries in England and Wales within a limited resource envelope.

The approach is commended to the Environment Agency and English Nature to assist them in the general management of estuary water quality and conservation interest. However, the approach is not appropriate for sites where detailed information has already been gathered, and ecological targets set i.e. SACs and SPAs.

The classification scheme is based on criteria that influence the biological response. The findings of one-off surveys (based on existing biological information and physical characteristics) already collated in JNCC reports would provide estuary "managers" with a valuable overview of English and Welsh estuaries.

It is recommended that the following physico-chemical characteristics should be included as classification criteria:

- **Nutrient Input:** The quantity of nutrients entering a system clearly influences the potential impact on biological communities. The assessment of nutrient loads relative to estuarine area or volume may provide a more interesting perspective on nutrient input.

- **Turbidity:** Turbidity levels affect the light availability and the potential response of autotrophic species to available nutrients, the numbers of bacteria and the dynamics of phosphorus.

- **Flushing Time:** The flushing time influences the retention time of nutrients within the estuaries and therefore the availability of the nutrients for uptake by autotrophs.

- **Tidal Range (relative to depth):** The bathymetry and tidal regime influence the water circulation and flushing rate, and so also have consequences for the stability of the substratum and the turbidity of the water column.

- **Risk of Stratification:** Stratification can be responsible for many nutrient impacts in estuaries, through its influence on nutrient circulation, phytoplankton bloom formation and oxygen depletion in the bottom waters.

- **Freshwater Input (relative to total estuary volume):** Freshwater input affects the nutrient delivery rate from diffuse sources, as well as the water circulation, turbidity levels and flushing time.

- **Bathymetry (Width:Depth and Inter-tidal: Sub-tidal Area ratios):** These key ratios, which describe the bathymetry of an estuary, which influence the relative response of benthic and pelagic autotrophic taxa.

To make an appropriate assessment, the data pertaining to these criteria must be analysed using appropriate techniques. The nature, quality and quantity of the data will determine what techniques could be applied, but these could include multivariate statistical analysis, tabulations or 'decision trees'.

However, it is recognised that existing data may not be adequate for a completely rigorous analysis, and that a simplified approach could be adopted such as a 'three factor' approach, or best expert judgement. The latter may ultimately provide the best practical option for such assessments.

5.3 Proposed EcoQOs for the 'Symptoms' of Eutrophication in Estuaries

Ecological Quality Objectives are suggested for different estuarine communities

The table below identifies key components of estuarine communities, and tentatively suggests Ecological Quality Objectives (EcoQOs) for each, which will need further development and testing to make them applicable to specific situations.

Community	**Ecological Quality Objective**
Micro/macroplankton	No deviation from structural and functional indices within the estuary.
Macroalgae	Prevention of: -the regular occurrence of contiguous mats of opportunistic algae in the inter-tidal regions or -any increasing scale in blooms over a period of *n* years or -the occurrence of odour problems/shoreline debris following the decay of algal mats or -the presence of extensive growth of epiphytic algae on sea-grasses.
Seagrasses	No persistent decline in areal coverage or productivity, relative to all estuarine vegetation over *n* years.
Saltmarshes	No persistent decline in the areal coverage or productivity relative to all estuarine vegetation over *n* years. No persistent increase in plant tissue nutrient levels over a period of *n* years.
Benthic Macrofauna	No development of communities indicative of organic enrichment *i.e.* at the degraded conditions of the Pearson-Rosenberg Continuum.
Fish	No creation of a water quality barrier to prevent fish migration, or fish kills from toxic blooms.
Birds	No inhibition of bird feeding by macroalgal bloom development, and no toxic effect on the palatability of prey.
Holistic Ecosystem Function	No deviation from holistic structural and functional indices.